APPLICATION FOR UNITED STATES LETTERS PATENT

for

CATHODE MATERIALS FOR SECONDARY (RECHARGEABLE) LITHIUM BATTERIES

by

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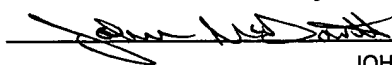**John B. Goodenough**

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BACKGROUND OF THE INVENTION

This application is a continuation-in-part of application Serial No. 08/840,523, filed April 21, 1997, now U.S. Pat. No. 5,910,382 which is a continuation-in-part of provisional patent application No. 60/032,346 filed December 4, 1996, and a continuation-in-part of provisional patent application No. 60/016,060, filed April 23, 1996. The entire text of each of the above-referenced disclosures is specifically incorporated by reference herein without disclaimer. The Robert A. Welch Foundation, Houston, Texas, supported research related to the present invention.

1.   Field of the Invention

The present invention relates to secondary (rechargeable) alkali-ion batteries. More specifically, the invention relates to materials for use as electrodes for an alkali-ion battery. The invention provides transition-metal compounds having the ordered olivine, the modified olivine or the rhombohedral NASICON structure and containing the polyanion $(PO_4)^{3-}$ as at least one constituent for use as electrode material for alkali-ion rechargeable batteries.

2.   Description of the Related Art

Present-day lithium batteries use a solid reductant as the anode and a solid oxidant as the cathode. On discharge, the metallic anode supplies Li^+ ions to the Li^+–ion electrolyte and electrons to the external circuit. The cathode is typically an electronically conducting host into which Li^+ ions are inserted reversibly from the electrolyte as a guest species and charge-compensated by electrons from the external circuit. The chemical reactions at the anode and cathode of a lithium secondary battery must be reversible. On charge, removal of electrons from the cathode by an external field releases Li^+ ions back to the electrolyte to restore the parent host structure, and the addition of electrons to the anode by the external field attracts charge-compensating Li^+ ions back into the anode to restore it to its original composition.

Present-day rechargeable lithium-ion batteries use a coke material into which lithium is inserted reversibly as the anode and a layered or framework transition-metal

-2-

oxide is used as the cathode host material (Nishi *et al.*, U.S. Patent 4,959,281). Layered oxides using Co and/or Ni are expensive and may degrade due to the incorporation of unwanted species from the electrolyte. Oxides such as $Li_{1\pm x}[Mn_2]O_4$, which has the $[M_2]O_4$ spinel framework, provide strong bonding in three dimensions and an interconnected interstitial space for lithium insertion. However, the small size of the O^{2-} ion restricts the free volume available to the Li^+ ions, which limits the power capability of the electrodes. Although substitution of a larger S^{2-} ion for the O^{2-} ion increases the free volume available to the Li^+ ions, it also reduces the output voltage of an elementary cell.

A host material that will provide a larger free volume for Li^+-ion motion in the interstitial space would allow realization of a higher lithium-ion conductivity σ_{Li}, and hence higher power densities. An oxide is needed for output voltage, and hence higher energy density. An inexpensive, non-polluting transition-metal atom would make the battery environmentally benign.

SUMMARY OF THE INVENTION

The present invention meets these goals more adequately than previously known secondary battery cathode materials by providing oxides containing larger tetrahedral oxide polyanions forming 3D framework host structures with octahedral-site transition-metal oxidant cations, such as iron, that are environmentally benign.

The present invention provides electrode material for a rechargeable electrochemical cell comprising an anode, a cathode and an electrolyte. The cell may additionally include an electrode separator. As used herein, "electrochemical cell" refers not only to the building block, or internal portion, of a battery but is also meant to refer to a battery in general. Although either the cathode or the anode may comprise the material of the invention, the material will preferably be useful in the cathode.

Generally, in one aspect, the invention provides an ordered olivine compound having the general formula $LiMPO_4$, where M is at least one first row transition-metal cation. The alkali ion Li^+ may be inserted/extracted reversibly from/to the electrolyte of the battery to/from the interstitial space of the host MPO_4 framework of the ordered-olivine structure as the transition-metal M cation (or combination of cations) is reduced/oxidized by charge-compensating electrons supplied/removed by the external

-3-

circuit of the battery in, for a cathode material, a discharge/charge cycle. In particular, M will preferably be Mn, Fe, Co, Ti, Ni or a combination thereof. Examples of combinations of the transition-metals for use as the substituent M include, but are not limited to, $Fe_{1-x}Mn_x$, and $Fe_{1-x}Ti_x$, where $0 < x < 1$.

5   Preferred formulas for the ordered olivine electrode compounds of the invention include, but are not limited to $LiFePO_4$, $LiMnPO_4$, $LiCoPO_4$, $LiNiPO_4$, and mixed transition-metal comounds such as $Li_{1-2x}Fe_{1-x}Ti_xPO_4$ or $LiFe_{1-x}Mn_xPO_4$, where $0 < x < 1$. However, it will be understood by one of skill in the art that other compounds having the general formula $LiMPO_4$ and an ordered olivine structure are included within the scope of

10   the invention.

The electrode materials of the general formula $LiMPO_4$ described herein typically have an ordered olivine structure having a plurality of planes defined by zigzag chains and linear chains, where the M atoms occupy the zigzag chains of octahedra and the Li atoms occupy the linear chains of alternate planes of octahedral sites.

15   The present invention additionally provides electrode material for a rechargeable electrochemical cell including an anode, a catrode and an electrolyte where the material has a modified olivine strucutre. The pristine olivine structure of $LiMPO_4$ may be modified either on the anionic site or on the cationic site to provide an alternative lithium insertion-type. It is also envisioned that the pristine olivine structure may be modified on

20   both the anionic and the cationic sites. Preferably, the structure is modified by aliovalent or isocharge substitutions to provide better lithium ion diffusitivity and electronic conductivity.

In general, "isocharge substitutions" refers to substitution of one element on a given crystallographic site with an element having a similar charge. For example, Mg^{2+} is

25   considered similarly isocharge with Fe^{2+} and V^{5+} is similarly isocharge with P^{5+}. Likewise, PO_4^3 tetrahedra can be substituted with VO_4^3 tetrahedra. "Aliovalent substitution" refers to substitution of one element on a given crystallographic site with an element of a different valence or charge. One example of an aliovalent substitution would be Cr^{3+} or Ti^{4+} on an Fe^{2+} site. Another example would be Li^+ on a Fe^{2+} site. These cathode

-4-

materials will generally have an olivine structure based on iron or manganese derivatives whose general formula is:

$$Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$$

where

M may be Fe^{2+} or Mn^{2+} or mixtures thereof;

D may be a metal in the +2 oxidation state, preferably Mg^{2+}, Ni^{2+}, Co^{2+}, Zn^{2+}, Cu^{2+}, or Ti^{2+};

T may be a metal in the +3 oxidation state, preferably Al^{3+}, Ti^{3+}, Cr^{3+}, Fe^{3+}, Mn^{3+}, Ga^{3+}, Zn^{3+}, or V^{3+};

Q may be a metal in the +4 oxidation state, preferably Ti^{4+}, Ge^{4+}, Sn^{4+}, or V^{4+};

R may be a metal in the +5 oxidation state, preferably V^{5+}, Nb^{5+}, or Ta^{5+};

In this preferred embodiment, M, D, T, Q and R reside in octahedral sites. The additional coefficients may be defined as follows: x represents the degree of intercalation during operation of the electrode material; y represents the fraction of lithium ions on the initial Fe^{2+} sites; d represents the fraction of divalent ions (noted as D) on the initial Fe^{2+} sites; t represents the fraction of trivalent ions (noted as T) on the initial Fe^{2+} sites; q represents the fraction of tetravalent ions (noted as Q) on the initial Fe^{2+} sites; r represents the fraction of pentavalent ions (noted as R) on the initial Fe^{2+} sites; p represents the fraction of hexavalent suflur (as discrete SO_4^{2-} tetrahedra) on the initial P^{5+} sites; s represents the fraction of tetravalent silicon (as discrete SiO_4^{2-} tetrahedra) on the initial P^{5+} sites; and v represents the fraction of pentavalent vanadium ions on the initial P^{5+} sites.

The conditions for site occupancy and electroneutrality imply the following:

$$0 \leq x \leq 1;$$

$$y + d + t + q + r \leq 1;$$

$$P + s + v \leq 1;\ and$$

$$3 + s - p = x - y + t + 2q + 3r.$$

-5-

x, y, d, t, q, r, p, s, and v may be between 0 (zero) and 1 (one), with at least one of y, d, t, q, r, p, s, or v differing from 0. In a preferred embodiment y, d, t, q, r, and v may vary between 0 (zero) and 0.2 (2/10) and r and s may vary between 0 (zero) and 0.5 (1/2).

The invention further provides an electrochemical cell or battery having at least one positive and one negative electrode. At least one positive electrode in this embodiment contains the $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ material described above. Further, at least one negative electrode contains a source of lithium ion at a high chemical activity. The phrase "high chemical activity" is generally understood in the art to refer to an electrode whose mean voltage during operation is not more positive than 2 volts versus the Li^+/Li^o couple.

Preferably, at least one negative electrode will contain metallic lithium, a lithium alloy, a lithium-carbon intercalation compound, a lithium-transition metal mixed nitride of antifluorite, or a lithium-titanium spinel $Li_{1+x+z}Ti_{2-x}O_4$, where $0 \leq x \leq 1/3$ and $0 \leq z \leq 1 - 2x$. It will be understood by those of skill in the art that the term "a" used before a compound encompasses structures containing more than one of that type of compound. For example, "a lithium-transition metal mixed nitride of antifluorite" encompasses mixtures of more than one of this type of compound and "a lithium-titanium spinel" encompasses solid solutions and/or mixtures of more than one of this type of compound with other spinels.

Alternatively, the electrochemical cell of the invention may contain an intercalation material with fast diffusion kinetics in the positive electrode containing the $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ material described above. The phrase "fast diffusion kinetics" is generally understood in the art as referring to a material able to sustain a specific current of at least 10 mA per gram of material with more than 80% utilization of the capacity at the temperature of operation. Preferably, the intercalation material with fast diffusion kinetics may be a lamellar dichalcognenide, a vanadium oxide VO_x where $2.1 \leq x \leq 2.5$, or a NASICON-related material such as $Li_3Fe_2(PO_4)_3$ or $Li_{3-x}Fe_{2-x}Ti_x(PO_4)_3$, where x represents the degree of substitution of Fe^{3+} by Ti^{4+}.

-6-

In other preferred aspects, the electrochemical cell of the invention will include a conductive additive in at least one positive electrode. The conductive additive may preferably be carbon.

In other aspects, it is envisioned that the electrochemical cell of the invention includes at least one positive electrode containing the $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ material described above and a polymeric binder. In certain preferred aspects, this positive electrode may additionally include a conductive additive, such as carbon.

Preferably, the polymeric binder may be a homopolymer or copolymer of tetrafluoroethylene, an ethylene-propylene-diene terpolymer, a polyether, a polyester, a methylmethacrylate-based polymer, an acrylonitrile-based polymer, or a vinylidene fluoride-based polymer. It is contemplated that the polymeric binder for use in conjunction with the present invention may be crosslinked, but those of skill in the art will appreciate that cross-linkage is not essential. The term "crosslinked" refers to the presence of physical or chemical bonds between the polymer chains. Generally, those skilled in the art measure crosslinkage in terms of the number of crosslinks per cubic centimeter. The polymeric binder for use in conjunction with the present invention will preferably have a cross-linkage of between 10^{18} and 10^{20} inter-chain bonds per cubic centimeter.

Alternatively, the polymeric binder may possess ionic conductivity. Ionic conductivity is generally understood in the art to be the ability to carry a current due to the motion of ions. Preferred values of ionic conductivity are between about 10^{-7} and about 10^{-2} (Scm^{-1}). In certain embodiments, the polymeric binder may be swollen by an aprotic solvent which contain a salt, the cation of which is at least in part Li^+. The aprotic solvent may preferably be ethylene carbonate, propylene carbonate, dimethylcarbonate, diethylcarbonate, methyl-ethylcarbonate, γ-butyrolactone, a tetraalkylsulfamide, or a dialkylether of a mono-, di-, tri-, tetra- or higher oligo-ethylene glycol of molecular weight lower or equal to 2000 and mixtures thereof.

The invention further provides a variable optical transmission device which is constructed from transparent semi-conductor coated glass or plastic and includes two

-7-

electrodes separated by a solid or gel electrolyte. In this embodiment, at least one electrode contains the $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ material as described above. Preferably, the $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ compound of the invention is layed on a transparent semi-conductor coated glass or plastic in a thin film. It is preferred that the semi-conductor be coated onto the glass or plastic at a thickness of between 200 and 10^4 Ångströms (Å) or between 20 and 10^4 nanometers (nm). The material of the invention may be placed onto the glass or plastic, for example, using a vacuum deposition technique, by sputtering, or from a sol-gel precursor. The techniques for placing the compound of the invention onto the glass or plastic are well known to those skilled in the art. Preferred techniques include sputtering, chemical vapor deposition (CVD) from organometallic precursors like metal hexafluoroacetylacetonates and organic phosphates or silicates, sol-gel from hydrolysis-condensation of metal alkoxides in water-organic solutions in the presence of phosphoric acid and organosiloxanes.

It is preferred that the glass for use in conjunction with the present invention be conventional optical quality glazing. Preferred plastics include high transparency, high mechanical strength material like polyethylene terephatalate (Mylar®). The transparent semi-conductor is contemplated to be virtually any transparent semi-conductor but is preferably antimony- or fluorine-doped tin oxide, tin- or fluorine-doped indium oxide, or non-stoichiometric zinc oxide.

In another aspect, the invention provides electrode materials for a rechargeable electrochemical cell comprising an anode, a cathode and an electrolyte, with or without an electrode separator, where the electrode materials comprise a rhombohedral NASICON material having the formula $Y_xM_2(PO_4)_3$, where $0 \le x \le 5$. Preferably, the compounds of the invention will be useful as the cathode of a rechargeable electrochemical cell. The alkali ion Y may be inserted from the electrolyte of the battery to the interstitial space of the rhombohedral $M_2(XO_4)_3$ NASICON host framework as the transition-metal M cation (or combination of cations) is reduced by charge-compensating electrons supplied by the external circuit of the battery during discharge with the reverse process occurring during charge of the battery. While it is contemplated that the materials of the invention may

-8-

consist of either a single rhombohedral phase or two phases, *e.g.* orthorhombic and monoclinic, the materials are preferably single-phase rhombohedral NASICON compounds. Generally, M will be at least one first-row transition-metal cation and Y will be Li or Na. In preferred compounds, M will be Fe, V, Mn, or Ti and Y will be Li.

Redox energies of the host M cations can be varied by a suitable choice of the XO_4 polyanion, where X is taken from Si, P, As, or S and the structure may contain a combination of such polyanions. Tuning of the redox energies allows optimization of the battery voltage with respect to the electrolyte used in the battery. The invention replaces the oxide ion O^{2-} of conventional cathode materials by a polyanion $(XO_4)^{m-}$ to take advantage of (1) the larger size of the polyanion, which can enlarge the free volume of the host interstitial space available to the alkali ions, and (2) the covalent X-O bonding, which stabilizes the redox energies of the M cations with M-O-X bonding so as to create acceptable open-circuit voltages V_{oc} with environmentally benign Fe^{3+}/Fe^{2+} and/or Ti^{4+}/Ti^{3+} or V^{4+}/V^{3+} redox couples.

Preferred formulas for the rhombohedral NASICON electrode compounds of the invention include, but are not limited to those having the formula $Li_{3+x}Fe_2(PO_4)_3$, $Li_{2+x}FeTi(PO_4)_3$, $Li_xTiNb(PO_4)_3$, and $Li_{1+x}FeNb(PO_4)_3$, where $0 < x < 2$. It will be understood by one of skill in the art that Na may be substituted for Li in any of the above compounds to provide cathode materials for a Na ion rechargeable battery. For example, one may employ $Na_{3+x}Fe_2(PO_4)_3$, $Na_{2+x}FeTi(PO_4)_3$, $Na_xTiNb(PO_4)_3$ or $Na_{1+x}FeNb(PO_4)_3$, where $0 < x < 2$, in a Na ion rechargeable battery. In this aspect, Na^+ is the working ion and the anode and electrolyte comprise a Na compound.

Compounds of the invention having the rhombohedral NASICON structure form a framework of MO_6 octahedra sharing all of their corners with XO_4 tetrahedra (X = Si, P, As, or S), the XO_4 tetrahedra sharing all of their corners with octahedra. Pairs of MO_6 octahedra have faces bridged by three XO_4 tetrahedra to form "lantern" units aligned parallel to the hexagonal *c*-axis (the rhombohedral [111] direction), each of these XO_4 tetrahedra bridging to two different "lantern" units. The Li^+ or Na^+ ions occupy the interstitial space within the $M_2(XO_4)_3$ framework. Generally, $Y_xM_2(XO_4)_3$ compounds with the rhombohedral NASICON framework may be prepared by solid-state reaction of

stoichiometric proportions of the Y, M, and XO_4 groups for the desired valence of the M cation. Where Y is Li, the compounds may be prepared indirectly from the Na analog by ion exchange of Li^+ for Na^+ ions in a molten $LiNO_3$ bath at 300°C. For example, rhombohedral $LiTi_2(PO_4)_3$ may be prepared from intimate mixtures of Li_2CO_3 or $LiOH \cdot H_2O$, TiO_2, and $NH_4H_2PO_4 \cdot H_2O$ calcined in air at 200°C to eliminate H_2O and CO_2 followed by heating in air for 24 hours near 850°C and a further heating for 24 hours near 950°C. However, preparation of $Li_3Fe_2(PO_4)_3$ by a similar solid-state reaction gives the undesired monoclinic framework. To obtain the rhombohedral form, it is necessary to prepare rhombohedral $Na_3Fe_2(PO_4)_3$ by solid-state reaction of $NaCO_3$, $Fe\{CH_2COOH\}_2$ and $NH_4H_2PO_4 \cdot H_2O$, for example. The rhombohedral form of $Li_3Fe_2(PO_4)_3$ is then obtained at 300°C by ion exchange of Li^+ for Na^+ in a bath of molten $LiNO_3$. It will be understood by one of skill in the art that the rhombohedral Na compounds will be useful as cathode materials in rechargeable Na ion batteries.

In another aspect of the invention, the rhombohedral NASICON electrode compounds may have the general formula $Y_xM_2(PO_4)_y(XO_4)_{3-y}$, where $0 < y \leq 3$, M is a transition-metal atom, Y is Li or Na, and X = Si, As, or S and acts as a counter cation in the rhombohedral NASICON framework structure. In this aspect, the compound comprises a phosphate anion as at least part of an electrode material. In preferred embodiments, the compounds are used in the cathode of a rechargeable battery. Preferred compounds having this general formula include, but are not limited to $Li_{1+x}Fe_2(SO_4)_2(PO_4)$, where $0 \leq x \leq 1$.

The rhombohedral NASICON compounds described above may typically be prepared by preparing an aqueous solution comprising a lithium compound, an iron compound, a phosphate compound and a sulfate compound, evaporating the solution to obtain dry material and heating the dry material to about 500°C. Preferably, the aqueous starting solution comprises $FeCl_3$, $(NH_4)_2SO_4$, and LiH_2PO_4.

In a further embodiment, the invention provides electrode materials for a rechargeable electrochemical cell comprising an anode, a cathode and an electrolyte, with or without an electrode separator, where the electrode materials have a rhombohedral NASICON structure with the general formula $A_{3-x}V_2(PO_4)_3$. In these compounds, A may

-10-

be Li, Na or a combination thereof and $0 \leq x \leq 2$. In preferred embodiments, the compounds are a single-phase rhombohedral NASICON material. Preferred formulas for the rhombohedral NASICON electrode compounds having the general formula $A_{3-x}V_2(PO_4)_3$ include, but are not limited to those having the formula $Li_{2-x}NaV_2(PO_4)_3$, where $0 \leq x \leq 2$.

The rhombohedral NASICON materials of the general formula $A_{3-x}V_2(PO_4)_3$ may generally be prepared by the process outlined in FIG. 9. Alternatively, $Li_2NaV_2(PO_4)_3$ may be prepared by a direct solid-state reaction from $LiCO_3$, $NaCO_3$, $NH_4H_2PO_4 \cdot H_2O$ and V_2O_3.

In a further aspect, the invention provides a secondary (rechargeable) battery where an electrochemical cell comprises two electrodes and an electrolyte, with or without an electrode separator. The electrodes are generally referred to as the anode and the cathode. The secondary batteries of the invention generally comprise as electrode material, and preferably as cathode material, the compounds described above. More particularly, the batteries of the invention have a cathode comprising the ordered olivine compounds described above or the rhombohedral NASICON compounds described above.

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings form part of the present specification and are included to demonstrate further certain aspects of the present invention. The invention may be better understood by reference to one or more of these drawings in combination with the detailed description of specific embodiments presented herein.

FIG. 1.   FIG. 1 shows a typical polarization curve for the battery voltage V vs. the I delivered across a load. The voltage drop $(V_{oc} - V) \equiv \eta(I)$ of a typical curve is a measure of the battery resistance $R_b(I)$. The interfacial voltage drops saturate in region (i). The slope of the curve in region (ii) is $dV/dI \approx R_{el} + R_c$ (A) $+ R_c$ (C), the sums of the electrolyte resistance R_{el} and the current-collector resistances at the anode and cathode. Region (iii) is diffusion-limited. At the higher currents I, normal processes do not bring

-11-

ions to or remove them from the electrode/electrolyte interfaces rapidly enough to sustain an equilibrium reaction.

FIG. 2A, 2B and 2C. FIG. 2A shows discharge/charge curves at 0.05 $mA \cdot cm^{-2}$ (0.95 $mA \cdot g^{-1}$) for the olivine $Li_{1-x}FePO_4$ as cathode and lithium as anode. A plateau at 3.4V corresponds to the Fe^{3+}/Fe^{2+} redox couple relative to the lithium anode. A plateau at 4.1 V corresponds to the Mn^{3+}/Mn^{2+} couple. FIG. 2B shows discharge/charge curves at 0.05 $mA \cdot cm^{-2}$ (1.13 $mA \cdot g^{-1}$) for the olivine $Li_{1-x}Fe_{0.5}Mn_{0.5}PO_4$ as cathode relative to a lithium anode. FIG. 2C shows discharge/charge curves vs. lithium at 0.05 $mA \cdot cm^{-2}$ (0.95 $mA \cdot g^{-1}$) for the olivine Li_xFePO_4.

FIG. 3. FIG. 3 shows discharge/charge curves of an $FePO_4/LiClO_4$ + PC + DME/Li coin cell at 185 $mA \cdot g^{-1}$ for $FePO_4$ prepared by chemical extraction of Li (delithiation) from $LiFePO_4$.

FIG. 4. Schematic representation of the motion of $LiFePO_4/FePO_4$ interface on lithium insertion in to a particle of $FePO_4$.

FIG. 5A and 5B. FIG. 5A shows the rhombohedral $R3c$ (NASICON) framework structure of $Li_3Fe_2(PO_4)_3$ prepared by ion exchange from $Na_3Fe_2(PO_4)_3$; FIG. 5B shows the monoclinic $P2_1/n$ framework structure of $Li_3Fe_2(PO_4)_3$ prepared by solid-state reaction.. The large, open three-dimensional framework of FeO_6 octahedra and PO_4 tetrahedra allows an easy diffusion of the lithium ions.

FIG. 6A and 6B. FIG. 6A shows discharge/charge curves vs. lithium at 0.1 $mA \cdot cm^{-2}$ for rhombohedral $Li_{3+x}Fe_2(PO_4)_3$ where $0 < x < 2$. The shape of the curve for lithium insertion into rhombohedral $Li_{3+x}Fe_2(PO_4)_3$ is surprisingly different from that for the monoclinic form. However, the average V_{oc} at 2.8 V remains the same. The Li^+-ion distribution in the interstitial space appears to vary continuously with x with a high degree of disorder. FIG. 6B shows discharge/charge curves vs. lithium at 0.1 $mA \cdot cm^{-2}$ for monoclinic $Li_{3+x}Fe_2(PO_4)_3$ where $0 < x < 2$.

FIG. 7A and 7B. FIG. 7A shows discharge curves vs. a lithium anode at current densities of 0.05-0.5 $mA \cdot cm^{-2}$ for rhombohedral $Li_{3+x}Fe_2(PO_4)_3$. A reversible capacity loss on increasing the current density from 0.05 to 0.5 $mA \cdot cm^{-2}$ is shown. This loss is much reduced compared to what is encountered with the monoclinic system. FIG.

-12-

.7B shows discharge curves at current densities of 0.05-0.5 mA $\cdot$ cm^{-2} for monoclinic Li$_{3+x}$Fe$_2$(PO$_4$)$_3$.

FIG. 8. FIG. 8 shows discharge/charge curves at 0.05 mA $\cdot$ cm^{-2} (0.95 mA $\cdot$ g^{-1}) for the rhombohedral Li$_x$NaV$_2$(PO$_4$)$_3$. Rhombohedral Li$_2$NaV$_2$(PO$_4$)$_3$ reversibly intercalates 1.5 Li per formula unit for a discharge capacity of 100 mAh $\cdot$ g^{-1} with average closed-circuit voltage of 3.8 V $vs.$ a lithium anode.

FIG. 9. FIG. 9 illustrates the solid-state synthesis of Li$_2$NaV$_2$(PO$_4$)$_3$ having the rhombohedral NASICON framework.

FIG. 10 FIG. 10 shows discharge/charge curves $vs.$ lithium at 0.1 mA$\cdot$cm^{-2} for rhombohedral Li$_{1+x}$Fe$_2$(PO$_4$)(SO$_4$)$_2$ where $0 \leq x \leq 2$.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Present-day secondary (rechargeable) lithium batteries use a solid reductant as the anode, or negative electrode, and a solid oxidant as the cathode, or positive electrode. It is important that the chemical reactions at the anode and cathode of a lithium secondary battery be reversible. On discharge, the metallic anode supplies Li$^+$ ions to the Li$^+$-ion electrolyte and electrons to the external circuit. The cathode is a host compound into/from which the working Li$^+$ ion of the electrolyte can be inserted/extracted reversibly as a guest species over a large solid-solubility range (Goodenough 1994). When the Li$^+$ ions are inserted as a guest species into the cathode, they are charge-compensated by electrons from the external circuit. On charge, the removal of electrons from the cathode by an external field releases Li$^+$ ions back to the electrolyte to restore the parent host structure. The resultant addition of electrons to the anode by the external field attracts charge-compensating Li$^+$ ions back into the anode to restore it to its original composition.

The present invention provides new materials for use as cathodes in lithium secondary (rechargeable) batteries. It will be understood that the anode for use with the cathode material of the invention may be any lithium anode material, such as a reductant host for lithium or elemental lithium itself. Preferably, the anode material will be a reductant host for lithium. Where both the anode and cathode are hosts for the reversible insertion or removal of the working ion into/from the electrolyte, the electrochemical cell

-13-

is commonly called a "rocking-chair" cell. An implicit additional requirement of a secondary battery is maintenance not only of the electrode/electrolyte interfaces, but also of electrical contact between host particles, throughout repeated discharge/recharge cycles.

Since the volumes of the electrode particles change as a result of the transfer of atoms from one to another electrode in a reaction, this requirement normally excludes the use of a crystalline or glassy electrolyte with a solid electrode. A non-aqueous liquid or polymer electrolyte having a large energy-gap window between its highest occupied molecular orbital (HOMO) and its lowest unoccupied molecular orbital (LUMO) is used with secondary lithium batteries in order to realize higher voltages. For example, practical quantities of very ionic lithium salts such as $LiClO_4$, $LiBF_4$ and $LiPF_6$ can be dissolved in empirically optimized mixtures of propylene carbonate (PC), ethylene carbonate (EC), or dimethyl carbonate (DMC) to provide acceptable electrolytes for use with the cathodes of the invention. It will be recognized by those of skill in the art that the $(ClO_4)^-$ anion is explosive and not typically suitable for commercial applications.

General Design Considerations

The power output P of a battery is the product of the electric current I delivered by the battery and the voltage V across the negative and positive posts (equation 1).

$$P = IV \tag{1}$$

The voltage V is reduced from its open-circuit value V_{oc} ($I = 0$) by the voltage drop IR_b due to the internal resistance R_b of the battery (equation 2).

$$V = V_{oc} - IR_b \tag{2}$$

The open-circuit value of the voltage is governed by equation 3.

-14-

$$V_{oc} = (\mu_A - \mu_C)/(-nF) < 5V \qquad (3)$$

In equation 3, n is the number of electronic charges carried by the working ion and F is Faraday's constant. The magnitude of the open-circuit voltage is constrained to $V_{oc} < 5V$ not only by the attainable difference $\mu_A - \mu_C$ of the electrochemical potentials of the anode reductant and the cathode oxidant, but also by the energy gap E_g between the HOMO (highest occupied molecular orbital) and the LUMO (lowest unoccupied molecular orbital) of a liquid electrolyte or by the energy gap E_g between the top of the valence band and the bottom of the conduction band of a solid electrolyte.

The chemical potential μ_A, which is the Fermi energy ε_F of a metallic-reductant anode or the HOMO of a gaseous or liquid reductant, must lie below the LUMO of a liquid electrolyte or the conduction band of a solid electrolyte to achieve thermodynamic stability against reduction of the electrolyte by the reductant. Similarly, the chemical potential μ_C, which is the LUMO of a gaseous or liquid oxidant or the Fermi energy of a metallic-oxidant cathode, must lie above the HOMO of a liquid electrolyte or the valence band of a solid electrolyte to achieve thermodynamic stability against oxidation of the electrolyte by the oxidant. Thermodynamic stability thus introduces the constraint

$$\mu_A - \mu_C \leq E_g \qquad (4)$$

as well as the need to match the "window" E_g of the electrolyte to the energies μ_A and μ_C of the reactants to maximize V_{oc}. It follows from equations 1 and 2 that realization of a high maximum power P_{max} (equation 5) requires, in addition to as high a V_{oc} as possible, a low internal battery resistance R_b (see equation 6).

$$P_{max} = I_{max} V_{max} \qquad (5)$$

$$R_b = R_{el} + R_{in}(A) + R_{in}(C) + R_c(A) + R_c(C) \qquad (6)$$

The electrolyte resistance R_{el} to the ionic current is proportional to the ratio of the effective thickness L to the geometrical area A of the interelectrode space that is filled with an electrolyte of ionic conductivity σ_i (equation 7).

$$R_{el} = (L/\sigma_i A) \tag{7}$$

Since ions move diffusively, σ_i (see equation 8) increases with temperature. A $\sigma_i \leq 0.1$ Scm^{-1} (the maximum σ_i represents the room-temperature protonic conductivity σ_H in a strong acid) at an operating temperature T_{op} dictates the use of a membrane separator of large geometrical area A and small thickness L.

$$\sigma_{Li} = (B/T)\exp(-E_\alpha/kT) \tag{8}$$

The resistance to transport of the working ion across the electrolyte-electrode interfaces is proportional to the ratio of the geometrical and interfacial areas at each electrode:

$$R_{in} \sim A/A_{in} \tag{9}$$

where the chemical reaction of the cell involves ionic transport across an interface, equation 9 dictates construction of a porous, small-particle electrode. Achievement and retention of a high electrode capacity, *i.e.*, utilization of a high fraction of the electrode material in the reversible reaction, requires the achievement and retention of good electronic contact between particles as well as a large particle-electrolyte interface area over many discharge/charge cycles. If the reversible reaction involves a first-order phase change, the particles may fracture or lose contact with one another on cycling to break a continuous electronic pathway to the current collector.

Loss of interparticle electrical contact results in an irreversible loss of capacity. There may also be a reversible capacity fade. Where there is a two-phase process (or even a sharp guest-species gradient at a diffusion front) without fracture of the particles, the

-16-

area of the interface (or diffusion front) decreases as the second phase penetrates the electrode particle. At a critical interface area, diffusion across the interface may not be fast enough to sustain the current I, so not all of the particle is accessible. The volume of inaccessible electrode increases with I, which leads to a diffusion-limited reversible capacity fade that increases with I. This problem becomes more important at lower ionic conductivity σ_{Li}.

The battery voltage V *vs.* the current I delivered across a load is called the polarization curve. The voltage drop $(V_{oc} - V) \equiv \eta(I)$ of a typical curve, FIG. 1, is a measure of the battery resistance (see equation 10).

$$R_b(I) = \eta(I)/I \tag{10}$$

On charging, $\eta(I) = (V_{app} - V_{oc})$ is referred to as an overvoltage. The interfacial voltage drops saturate in region (i) of FIG. 1; therefore in region (ii) the slope of the curve is

$$dV/dI \approx R_{el} + R_c \text{ (A)} + R_c \text{ (C)} \tag{11}$$

Region (iii) is diffusion-limited; at the higher currents I, normal processes do not bring ions to or remove them from the electrode/electrolyte interfaces rapidly enough to sustain an equilibrium reaction.

The battery voltage V *vs.* the state of charge, or the time during which a constant current I has been delivered, is called a discharge curve.

Cathode Materials

The cathode, or positive electrode, material of the present invention, for use in a secondary lithium battery, consists of a host structure into which lithium can be inserted reversibly. The maximum power output, P_{max} (see equation 5), that can be achieved by a cell depends on the open-circuit voltage $V_{oc} = \Delta E/e$ and the overvoltage $\eta(I)$ at the current I_{max} of maximum power

-17-

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-17-

$$V_{max} = V_{oc} - \eta(I_{max}) \tag{12}$$

ΔE is the energy difference between the work function of the anode (or the HOMO of the reductant) and that of the cathode (or the LUMO of the oxidant). In order to obtain a high V_{oc}, it is necessary to use a cathode that is an oxide or a halide. It is preferable that the cathode be an oxide in order to achieve a large V_{oc} and good electronic conductivity. To minimize $\eta(I_{max})$, the electrodes must be good electronic as well as ionic conductors and they must offer a low resistance to mass transfer across the electrode/electrolyte interface. To obtain a high I_{max}, it is necessary to have a large electrode/electrolyte surface area. In addition, where there is a two-phase interface within the electrode particle, the rate of mass transfer across this interface must remain large enough to sustain the current. This constraint tends to limit the electrode capacity more as the current increases.

Oxide host structures with close-packed oxygen arrays may be layered, as in $Li_{1-x}CoO_2$ (Mizushima, *et al.* 1980), or strongly bonded in three dimensions (3D) as in the manganese spinels $Li_{1-x}[Mn_2]O_4$ (Thackeray 1995; Thackeray *et al.* 1983; Thackeray *et al.* 1984; Guyomard and Tarascon 1992; and Masquelier *et al.* 1996). Li intercalation into a van der Waals gap between strongly bonded layers may be fast, but it can also be accompanied by unwanted species from a liquid electrolyte. On the other hand, strong 3D bonding within a close-packed oxygen array, as occurs in the spinel framework $[Mn_2]O_4$, offers too small a free volume for the guest Li^+ ions to have a high mobility at room temperature, which limits I_{max}. Although this constraint in volume of the interstitial space makes the spinel structure selective for insertion of Li^+ ions, it reduces the Li^+-ion mobility and hence Li^+-ion conductivity σ_{Li}. The oxospinels have a sufficiently high σ_{Li} to be used commercially in low-power cells (Thackeray *et al.*, 1983) but would not be acceptable for the high power cells of the insertion.

The present invention overcomes these drawbacks by providing cathode materials containing larger tetrahedral polyanions which form 3D framework host structures with octahedral-site transition-metal oxidant cations. In the cathode materials of the invention having the NASICON structure, the transition-metal ions are separated by the polyanions,

-18-

so the electronic conductivity is polaronic rather than metallic. Nevertheless, the gain in σ_{Li} more than offsets the loss in electronic conductivity.

Variation of the energy of a given cation redox couple from one compound to another depends on two factors: (a) the magnitude of the crystalline electric field at the cation, which may be calculated for a purely ionic model by a Madelung summation of the Coulomb fields from the other ions present, and (b) the covalent contribution to the bonding, which may be modulated by the strength of the covalent bonding at a nearest-neighbor counter cation. The stronger is the negative Madelung potential at a cation, the higher is a given redox energy of a cation. Similarly the stronger is the covalent bonding of the electrons at a transition-metal cation, the higher is a given redox energy of that cation. The lower the redox energy of the cation host transition-metal ion, the larger is V_{oc}.

The redox couples of interest for a cathode are associated with antibonding states of d-orbital parentage at transition-metal cations M or 4f-orbital parentage at rare-earth cations Ln in an oxide. The stronger is the cation-anion covalent mixing, the higher is the energy of a given LUMO/HOMO redox couple. Modulation of the strength of the cation-anion covalence at a given M or Ln cation by nearest-neighbor cations that compete for the same anion valence electrons is known as the inductive effect. Changes of structure alter primarily the Madelung energy as is illustrated by raising of the redox energy within a spinel $[M_2]O_4$ framework by about 1 eV on transfer of Li^+ ions from tetrahedral to octahedral interstitial sites. Changing the counter cation, but not the structure, alters primarily the inductive effect, as is illustrated by a lowering of the Fe^{3+}/Fe^{2+} redox energy by 0.6 eV on changing $(MoO_4)^{2-}$ or $(WO_4)^{2-}$ to $(SO_4)^{2-}$ polyanions in isostructural $Fe_2(XO_4)_3$ compounds. Raising the energy of a given redox couple in a cathode lowers the voltage obtained from cells utilizing a common anode. Conversely, raising the redox energy of an anode raises the cell voltage with respect to a common cathode.

The invention provides new cathode materials containing oxide polyanions, including the oxide polyanion $(PO_4)^{3-}$ as at least one constituent, for use in secondary (rechargeable) batteries. For example, the cathode materials of the present invention may have the general formula $LiM(PO_4)$ with the ordered olivine structure, the modified olivine

-19-

structure of $LiM(PO_4)$, or the more open rhombohedral NASICON framework structure. The cathode materials of the present invention have the general formula $LiM(PO_4)$ for the ordered olivine structure, the general formula $Li_{x+y}M_{1-(y+d+t+q+r)}D_dT_tQ_qR_r[PO_4]_{1-(p+s+v)}[SO_4]_p[SiO_4]_s[VO_4]_v$ for the modified olivine structure or $Y_xM_2(PO_4)_y(XO_4)_{3-y}$, for the rhombohedral NASICON framework structure. The parameters for the modified olivine structure are as follows:

M may be Fe^{2+} or Mn^{2+} or mixtures thereof;

D may be a metal in the +2 oxidation state, preferably Mg^{2+}, Ni^{2+}, Co^{2+}, Zn^{2+}, Cu^{2+}, or Ti^{2+};

T may be a metal in the +3 oxidation state, preferably Al^{3+}, Ti^{3+}, Cr^{3+}, Fe^{3+}, Mn^{3+}, Ga^{3+}, Zn^{3+}, or V^{3+};

Q may be a metal in the +4 oxidation state, preferably Ti^{4+}, Ge^{4+}, Sn^{4+}, or V^{4+};

R may be a metal in the +5 oxidation state, preferably V^{5+}, Nb^{5+}, or Ta^{5+}.

In this preferred embodiment x is the degree of intercalation during operation of the electrode material; y is the fraction of lithium ions on the initial Fe^{2+} sites; d is the fraction of divalent ions (noted as D) on the initial Fe^{2+} sites; t is the fraction of trivalent ions (noted as T) on the initial Fe^{2+} sites; q is the fraction of tetravalent ions (noted as Q) on the initial Fe^{2+} sites; r is the fraction of pentavalent ions (noted as R) on the initial Fe^{2+} sites; p is the fraction of hexavalent sulfur (as discrete SO_4^{2-} tetrahedra) on the initial P^{5+} sites; and s is the fraction of tetravalent silicon (as discrete SiO_4^{2-} tetrahedra) on the initial P^{5+} sites; v is the stoichiometric coefficient for V^{5+} residing in tetrahedral sites; and M, D, T, Q and R reside in octahedral sites.

The conditions for site occupancy an delectroneutrality imply:

$0 \leq x \leq 1$;

$y + d + t + q + r \leq 1$;

$p + s + v \leq 1$; and

$3 + s - p = x - y + t + 2q + 3r$.

-20-

Generally, x, y, d, t, q, r, p, s, and v may be between 0 (zero) and 1 (one), with at least one of y, d, t, q, r, p, s, or v differing from 0. Preferably, y, d, t, q, and v may vary between 0 (zero) and 0.2 (2/10) and r and s may vary between 0 (zero) and 0.5 (1/2).

In the rhombohedral NASICON framework structure, $0 < y \leq 3$, M is a transition-metal atom, Y is Li or Na and X = Si, As or S and acts as a counter cation.

The olivine structure of Mg_2SiO_4 consists of a slightly distorted array of oxygen atoms with Mg^{2+} ions occupying half the octahedral sites in two different ways. In alternate basal planes, they form zigzag chains of corner-shared octahedra running along the c-axis and in the other basal planes they form linear chains of edge-shared octahedra running also along the c-axis.

In the ordered $LiMPO_4$ olivine structures of the invention, the M atoms occupy the zigzag chains of octahedra and the Li atoms occupy the linear chains of the alternate planes of octahedral sites. In this embodiment of the present invention, M is preferably Mn, Fe, Co, Ni or combinations thereof. Removal of all of the lithium atoms leaves the layered $FePO_4$–type structure, which has the same *Pbnm* orthorhombic space group. These phases may be prepared from either end, *e.g.*, $LiFePO_4$ (triphylite) or $FePO_4$ (heterosite), by reversible extraction or insertion of lithium.

FIG. 2A, FIG. 2B and FIG. 2C show discharge/charge curves *vs.* lithium at 0.05 mA $\times$ cm^{-2} (0.95 mA $\times$ g^{-1} and 1.13 mA $\times$ g^{-1}, respectively) for $Li_{1-x}FePO_4$, $Li_{1-x}Fe_{0.5}Mn_{0.5}PO_4$ and Li_xFePO_4, respectively, where $0 \leq x \leq 5$. A plateau at 3.4 V corresponds to the Fe^{3+}/Fe^{2+} redox couple and a plateau at 4.1 V corresponds to the Mn^{3+}/Mn^{2+} couple. With $LiClO_4$ in PC and DME as the electrolyte, it is only possible to charge up a cathode to 4.3 V *vs.* a lithium anode, so it was not possible to extract lithium from $LiMnPO_4$, $LiCoPO_4$ and $LiNiPO_4$ with this electrolyte. However, in the presence of iron, the Mn^{3+}/Mn^{2+} couple becomes accessible. The inaccessibility is due to the stability of the Mn^{3+}/Mn^{2+}, Co^{3+}/Co^{2+} and Ni^{3+}/Ni^{2+} couples in the presence of the polyanion $(PO_4)^{3-}$. The relatively strong covalence of the PO_4 tetrahedron of the compounds of the present invention stabilizes the redox couples at the octahedral sites to give the high V_{oc}'s that are observed.

-21-

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Insertion of lithium into $FePO_4$ was reversible over the several cycles studied. FIG. 3 shows discharge/charge curves of $FePO_4/LiClO_4$ + PC + DME/Li coin cell at 185 mA · g^{-1} for $FePO_4$ prepared by chemical extraction of Li (delithiation) from $LiFePO_4$. The Li_xFePO_4 material of the present invention represents a cathode of good capacity and contains inexpensive, environmentally benign elements. While a nearly close–packed–hexagonal oxide–ion array apparently provides a relatively small free volume for Li^+–ion motion, which would seem to support only relatively small current densities at room temperature, increasing the current density does not lower the closed–circuit voltage V. Rather, it decreases, reversibly, the cell capacity. Capacity is easily restored by reducing the current.

As illustrated schematically in FIG. 4, lithium insertion proceeds from the surface of the particle moving inwards behind a two-phase interface. In the system shown, it is a $Li_xFePO_4/Li_{1-x}FePO_4$ interface. As the lithiation proceeds, the surface area of the interface shrinks. For a constant rate of lithium transport per unit area across the interface, a critical surface area is reached where the rate of total lithium transported across the interface is no longer able to sustain the current. At this point, cell performance becomes diffusion–limited. The higher the current, the greater is the total critical interface area and, hence, the smaller the concentration x of inserted lithium before the cell performance becomes diffusion–limited. On extraction of lithium, the parent phase at the core of the particle grows back towards the particle surface. Thus, the parent phase is retained on repeated cycling and the loss in capacity is reversible on lowering the current density delivered by the cell. Therefore, this loss of capacity does not appear to be due to a breaking of the electrical contact between particles as a result of volume changes, a process that is normally irreversible.

Electrode materials with the olivine structure $LiFePO_4$ (triphylite) and the quasi-isomorphous delithiated material $\square FePO_4$, have the advantage of an operating voltage of 3.5V vs. Li^+/Li°, i.e. in the stability window of both liquid and polymer electrolytes with a flat discharge (lithium intercalation) plateau (as seen in FIG.2A-2C??). It may be possible to increase the diffusion kinetics and electronic conductivity by using a modified olivine structure in an electrode. The absence of non-stoichiometry or mutual miscibility for both

-22-

phases ($LiFePO_4$ and $\square FePO_4$) in the materials with a pristine olivine structure may contribute to lower electronic conductivity than the materials having a modified olivine structure and to slower diffusion kinetics than may be achieved using materials with a modified olivine structure.

Thus, the invention additionally provides cathode materials where the pristine olivine structure of $LiM(PO_4)$ (M = Fe or Mn or their solid solutions) is modified either on the anionic site or on the cationic site, or on both, by aliovalent or isocharge substitutions, to provide better lithium ion diffusitivity and electronic conductivity. These substitutions allow for the coexistence of iron or manganese in two different oxidation states in the same phase. These substitutions may further introduce specific interactions with other elements having redox levels close to those of Fe and Mn (e.g., $Fe^{2+}/Ti^{4+} \Leftrightarrow Fe^{3+}/Ti^{3+}$, $Mn^{2+}/V^{5+} \Leftrightarrow Mn^{3+}/V^{4+}$ etc . . .). Both of these situations are favorable to electronic conductivity. Further, disorder on the anionic site provides preferential diffusion sites for Li^+. Similarly, partial substitution of phosphorus by vanadium, or to some extent by silicon, increases the lattice parameters, thereby increasing the size of the bottlenecks which tend to slow diffusion. The formation of non-stoichiometry domains with mixed valence states and/or transition-metal mediated electron hopping, as well as partial substitution of phosphorus sites, differentiates the modified olivine compounds from the $LiMPO_4/$ MPO_4 compounds in which the totality of Fe (Mn) is either in the +2 or +3 oxidation state.

The invention further provides new cathode materials exhibiting a rhombohedral NASICON framework. NASICON, as used herein, is an acronym for the framework host of a sodium superionic conductor $Na_{1+3x}Zr_2(P_{1-x}Si_xO_4)_3$. The compound $Fe_2(SO_4)_3$ has two forms, a rhombohedral NASICON structure and a related monoclinic form (Goodenough et al. 1976; Long et al. 1979). Each structure contains units of two FeO_6 octahedra bridged by three corner-sharing SO_4 tetrahedra. These units form 3D frameworks by the bridging SO_4 tetrahedra of one unit sharing corners with FeO_6 octahedra of neighboring $Fe_2(SO_4)_3$ elementary building blocks so that each tetrahedron shares corners with only octahedra and each octahedron with only tetrahedra. In the rhombohedral form, the building blocks are aligned parallel; while they are aligned nearly

-23-

perpendicular to one another in the monoclinic phase. The collapsed monoclinic form has a smaller free volume for Li^+–ion motion which is why the rhombohedral form is preferred. In these structures, the FeO_6 octahedra do not make direct contact, so electron transfer from an Fe^{2+} to an Fe^{3+} ion is polaronic and therefore activated.

5   $Li_xFe_2(SO_4)_3$ has been reported to be a candidate material for the cathode of a Li^+-ion rechargeable battery with a $V_{oc} = 3.6$ V vs. a lithium anode (Manthiram and Goodenough 1989). While the sulfates would seem to provide the desired larger free volume for Li, batteries using sulfates in the cathode material tend to exhibit phase-transition problems, lowering the electronic conductivity. The reversible lithium insertion

10 into both rhombohedral and monoclinic $Fe_2(SO_4)_3$ gives a flat closed-circuit voltage vs. a lithium anode of 3.6 V (Manthiram and Goodenough 1989; Okada et al. 1994; Nanjundaswamy et al. 1996). Neither parent phase has any significant solid solution with the orthorhombic lithiated phase $Li_2Fe_2(SO_4)_3$, which is derived from the rhombohedral form of $Fe_2(SO_4)_3$ by a displacive transition that leaves the framework intact. Powder X-

15 ray diffraction verifies that lithiation occurs via a two-phase process (Nanjundaswamy et al. 1996). Increasing the current density does not change significantly the closed-circuit voltage V, but it does reduce reversibly the capacity. The reduction in capacity for a given current density is greater for the motion of the lithiated interface. The interstitial space of the framework allows fast Li^+-ion motion, but the movement of lithium across the

20 orthorhombic/monoclinic interface is slower than that across the orthorhombic/rhombohedral interface, which makes the reversible loss of capacity with increasing current density greater for the monoclinic than for the rhombohedral parent phase.

The cathode materials of the invention avoid the phase transition of known sulfate

25 cathode materials by incorporating one or more phosphate ions as at least one of the constituents of the cathode material. The rhombohedral $R3c$ (NASICON) and monoclinic $P2_1/n$ framework structures of $Li_3Fe_2(PO_4)_3$ are similar to those for the sulfates described above, as illustrated in FIG. 5A and FIG. 5B.

A further embodiment of the invention is a rhombohedral NASICON cathode

30 material having the formula $A_{3-x}V_2(PO_4)_3$, where A may be Li, Na or a combination

-24-

thereof. Rhombohedral $A_{3-x}V_2(PO_4)_3$ reversibly intercalates 1.5 Li per formula unit for a discharge capacity of 100 mAh $\cdot$ g^{-1} with average closed-circuit voltage being 3.8 V $vs.$ a lithium anode (see FIG. 8). The voltage and capacity performances of the rhombohedral $A_{3-x}V_2(PO_4)_3$ compounds of the invention are comparable to the high-voltage cathode materials $LiMn_2O_4$ (4.0 V), $LiCoO_2$ (4.0 V) and $LiNiO_2$ (4.0 V). The large, open three-dimensional framework of VO_6 octahedra and PO_4 tetrahedra allows an easy diffusion of the lithium ions, making it attractive for high-power batteries. A further advantage of this material is that it includes a cheaper and less toxic transition-metal element (V) than the already developed systems using Co, Ni, or Mn.

EXAMPLES

Example 1.   Ordered Olivine $LiMPO_4$ Compounds

The ordered-olivine compound $LiFePO_4$ was prepared from intimate mixtures of stoichiometric proportions of Li_2CO_3 or $LiOH \cdot H_2O$, $Fe(CH_3CO_2)_2$ and $NH_4H_2PO_4 \cdot H_2O$; the mixtures were calcined at 300-350°C to eliminate NH_3, H_2O, and CO_2 and then heated in Ar at about 800°C for 24 hours to obtain LiFe PO_4. Similar solid-state reactions were used to prepare $LiMnPO_4$, $LiFe_{1-x}Mn_xPO_4$, $LiCoPO_4$ and $LiNiPO_4$. $FePO_4$ was obtained from $LiFePO_4$ by chemical extraction of Li from $LiFePO_4$. Charge/discharge curves for $Li_{1-x}FePO_4$ and discharge/charge cycles for Li_xFePO_4 gave similar results with a voltage of almost 3.5 V $vs.$ lithium for a capacity of 0.6 Li/formula unit at a current density of 0.05 mA$\cdot$cm^{2-} (See FIG. 2A and FIG. 2C). The electrolyte used had a window restricting voltages to V < 4.3 V. Li extraction was not possible from $LiMnPO_4$, $LiCoPO_4$, and $LiNiPO_4$ with the electrolyte used because these require a voltage V > 4.3 V to initiate extraction. However, Li extraction from $LiFe_{1-x}Mn_xPO_4$ was performed with $0 \leq x \leq 0.5$, and the Mn^{3+}/Mn^{2+} couple give a voltage plateau at 4.0 V $vs.$ lithium.

Example 2   Modified Olivine $LiMPO_4$ Compounds

The modified olivine compounds, $LiMPO_4$, were prepared from intimate mixtures of stoichiometric proportions of $Fe(C_2O_4)\cdot 2H_2O$ (Aldrich), LiH_2PO_4, $Li_2C_2O_4$ (Alpha Inorganics), $(NH_4)_2TiO(C_2O_4)_2 \cdot H_2O$ and polydiethoxysiloxane (Gelest) in isopropanol. In

-25-

particular, 12.95 grams of iron oxalate ($Fe(C_2O_4) \cdot 2H_2O$), 8.31 grams of lithium dihydrogen phosphate (LiH_2PO_4), 1.52 grams of lithium oxalate ($Li_2C_2O_4$), 2.94 grams of ammonium titanyl oxalate monohydrate (($NH_4)_2TiO(C_2O_4)_2 \cdot H_2O$) and 2.68 grams of polydiethyoxysiloxane in 120 milliliters (ml) of isopropanol were ball-milled in a polyethylene container with sintered zirconia balls for two days. The resulting slurry was evaporated to dryness and treated in a vacuum furnace at 350°C, the 700°C under argon (<6 ppm oxygen) to yield a compound with olivine structure of formula $Li_{1.1}Fe_{0.8}TiP_{0.8}Si_{0.2}O_4$.

The compound was delithiated with a solution of bromine in acetonitrile to $Li_{0.1}Fe_{0.8}TiP_{0.8}Si_{0.2}O_4$.

A solid-state button type cell was constructed using a 10^6 molecular weight polyethylene oxide-lithium bis(trifluoromethanesulfonylimide) electrolyte at an oxygen/lithium ratio of 20:1; the positive electrode was made from a 45/5/50 v/v composite of respectively the olivine material, Ketjenblack and an ionic binder of composition similar to that of the electrolyte, coated on a nickel current collector. The capacity was 1.2 mAh/cm^2. The negative electrode was lithium disc. At 80°C, 85% of the stoichiometric discharge capacity could be obtained and cycled reversibly at 100 mA/cm^2.

Example 3   Rhombohedral NASICON $Li_xM_2(PO_4)_3$ Structures

The inventors compared redox energies in isostructural sulfates with phosphates to obtain the magnitude of the change due to the different inductive effects of sulfur and phosphorus. Rhombohedral $Li_{1+x}Ti_2(PO_4)_3$ has been shown to exhibit a flat open–circuit voltage $V_{oc} = 2.5$ V vs. lithium, which is roughly 0.8 V below the Ti^{4+}/Ti^{3+} level found for $FeTi(SO_4)_3$. The flat voltage $V(x)$ is indicative of a two–phase process. A coexistence of rhombohedral and orthorhombic phases was found for $x = 0.5$ (Delmas and Nadiri 1988; Wang and Hwu 1992). $Li_{2+x}FeTi(PO_4)_3$ of the present invention remains single phase on discharge.

All three phosphates $Li_3M_2(PO_4)_3$, where M = Fe, Fe/V, or V, have the monoclinic $Fe_2(SO_4)_3$ structure if prepared by solid-state reaction. The inventors have found that these compounds exhibit a rhombohedral structure when prepared by ion exchange in $LiNO_3$ at 300°C from the sodium analog $Na_3Fe_2(PO_4)_3$. The discharge/charge curve of

-26-

FIG. 6A for lithium insertion into rhombohedral $Li_{3+x}Fe_2(PO_4)_3$ exhibits an average V_{oc} of 2.8 V. This is surprisingly different from the curves for the monoclinic form (See FIG. 6B). The inventors have found that up to two lithiums per formula unit can be inserted into $Li_3Fe_2(PO_4)_3$, leading to $Li_5Fe_2(PO_4)_3$. The Li^+–ion distribution in the interstitial space of $Li_{3+x}Fe_2(PO_4)_3$, where $0 < x < 2$, appears to vary continuously with x with a high degree of disorder. FIG. 7A shows a reversible capacity loss on increasing the current density from 0.05 to 0.5 mA $\cdot$ cm^{-2}. A reversible discharge capacity of 95 mAh $\cdot$ g^{-1} is still observed for rhombohedral $Li_{3+x}Fe_2(PO_4)_3$ at a current density of 20 mA $\cdot$ g^{-1}. This is much reduced compared to what is encountered with the monoclinic system (See FIG. 7B). With a current density of 23 mA $\cdot$ g^{-1} (or 1 mA $\cdot$ cm^{-2}), the initial capacity of 95 mAh $\cdot$ g^{-1} was maintained in a coin cell up to the 40th cycle.

Another cathode material of the present invention, $Li_2FeTi(PO_4)_3$, having the NASICON framework was prepared by solid-state reaction. This material has a voltage ranging from 3.0 to 2.5 V.

Rhombohedral $TiNb(PO_4)_3$ can be prepared by solid-state reaction at about 1200°C. Up to three Li atoms per formula unit can be inserted, which allows access to the Nb^{4+}/Nb^{3+} couple at 1.8 V vs. lithium for $x > 2$ in $Li_x TiNb(PO_4)_3$. Two steps are perhaps discernible in the compositional range $0 < x < 2$; one in the range of $0 < x < 1$ corresponds to the Ti^{4+}/Ti^{3+} couple in the voltage range 2.5 V $< V <$ 2.7 V and the other for $1 < X < 2$ to the Nb^{5+}/Nb^{4+} couple in the range 2.2 V $< V <$ 2.5 V. It appears that these redox energies overlap. This assignment is based on the fact that the Ti^{4+}/Ti^{3+} couple in $Li_{1+x}Ti_2(PO_4)_3$ gives a flat plateau at 2.5 V due to the presence of two phases, rhombohedral $LiTi_2 (PO_4)_3$ and orthorhombic $Li_3Ti_2 (PO_4)_3$. The presence of Nb in the structure suppresses the formation of the second phase in the range $0 < x < 2$.

Rhombohedral $LiFeNb(PO_4)_3$ and $Li_2FeTi(PO_4)_3$ can be prepared by ion exchange with molten $LiNO_3$ at about 300°C from $NaFeNb(PO_4)_3$ and $Na_2FeTi(PO_4)_3$, respectively. Two Li atoms per formula unit can be inserted reversibly into $Li_{2+x}FeTi(PO_4)_3$ with a little loss of capacity at 0.5 mA$\cdot$cm^{-2}. Insertion of the first Li atom in the range 2.7 V$<V<$3.0 V corresponds to the Fe^{3+}/Fe^{2+} redox couple and of the second Li atom in the range of 2.5 V$<V<$2.7 V to an overlapping Ti^{4+}/Ti^{3+} redox couple. The insertion of lithium into Li_{1+x}

-27-

Fenb $(PO_4)_3$ gives a V vs. x curve that further verifies the location of the relative positions of the Fe^{3+}/Fe^{2+}, Nb^{5+}/Nb^{4+} redox energies in phosphates with NASICON-related structures. It is possible to insert three lithium atoms into the structure; and there are three distinct plateaus corresponding to Fe^{3+}/Fe^{2+} at 2.8 V, Nb^{5+}/Nb^{4+} at 2.2 V, and Nb^{4+}/Nb^{5+} at 1.7 V vs. lithium in the discharge curve.

The rhombohedral $A_{3-x}V_2(PO_4)_3$ compounds of the invention can be prepared by ionic exchange from the monoclinic sodium analog $Na_3V_2(PO_4)_3$. The inventors were also able to prepare the rhombohedral $Li_2NaV_2(PO_4)_3$ with the NASICON framework by a direct solid-state reaction (FIG. 9). The discharge/charge curves at 0.05 mA $\cdot$ cm^{-2} (0.95 mA $\cdot$ g^{-1}) for the rhomobhedral $Li_xNaV_2(PO_4)_3$ are shown in FIG. 8.

The rhombohedral $LiFe_2(SO_4)_2(PO_4)$ may be prepared by obtaining an aqueous solution comprising $FeCl_3$, $(NH_4)_2SO_4$, and LiH_2PO_4, stirring the solution and evaporating it to dryness, and heating the resulting dry material to about 500°C. Discharge/charge curves vs. lithium at 0.1 mA $\cdot$ cm^{-2} for rhombohedral $Li_{1+x}Fe_2(PO_4)(SO_4)_2$, where $0 < x < 3$, are shown in FIG. 10.

All of the compositions and/or methods disclosed and claimed herein can be made and executed without undue experimentation in light of the present disclosure. While the compositions and methods of this invention have been described in terms of preferred embodiments, it will be apparent to those of skill in the art that variations may be applied to the compositions and/or methods and in the steps or in the sequence of steps of the method described herein without departing from the concept, spirit and scope of the invention. More specifically, it will be apparent that certain agents which are both chemically and structurally related may be substituted for the agents described herein to achieve similar results. All such substitutions and modifications apparent to those skilled in the art are deemed to be within the spirit, scope and concept of the invention as defined by the appended claims.

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